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Investigation of ecological constraints influence on competitiveness of nuclear power plants

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Abstract

The purpose of the present study is to compare economic efficiency of nuclear power plants and plants on fossil fuel for short-term and long-term (until 2050) perspective and further forecasts specification of nuclear power generation development in Russia and in the world on the background of world energy as a whole.

Technical and economic indicators of power plants of different types are systematized taking into account their uncertainty margins. Competitiveness of power plants of different types was estimated according to cost of electricity produced. The cost of electricity is presented as the sum of components taking into account cost of construction, operational costs, decommissioning costs, fuel costs, and payments for emissions. It was demonstrated that if payment for emissions are not included power sources of all the examined types can be competitive on the energy markets (under certain conditions), including the markets in Russia. If payments for greenhouse gases emission are included in the calculations nuclear power plants become the most cost effective power source.

Additional comparison of power sources of different types taking into account system effects was performed using the GEM model (global energy model). The calculations demonstrated that under all three examined scenarios the scales of nuclear energy use are expected to increase. This growth will be the most significant in case of imposition of strict environmental restrictions (approximately by 4 times by the middle of the century in Russia and by 3.5 times in the world).

Keywords: Nuclear power generation; Electricity costs; Environmental constraints; Payment for emissions; Economic efficiency; Energy model; Forecast.

Environmental constraints and payments for carbon dioxide emissions

Active discussion is ongoing during several recent decades about the effects produced by human economic activities on Earth climate. In particular, it is stated in the reports of the Intergovernmental Panel on Climate Change (IPCC) [1] that probability is high that man-induced impact on the climatic system is the dominating reason of climate warming observed from the middle of the 20th century. Emissions of greenhouse gases (first of all emissions of carbon dioxide), if continued on the existing level and, even more so, in case of increase of these emissions, will result in the further growth of concentrations of pollutants in atmosphere, increase of average global temperature on the air–ground interface and the diverse negative consequences for nature, economy and human health.

Even reduced intensity of emissions of greenhouse gases will not prevent climate changes due to the inertia of the climatic system explained by the preservation of previously accumulated emission in atmosphere. Imposing limitation of 2°C on the increase of global average temperature (comparable with pre-industrial level) (such increase can be regarded as not leading to catastrophic consequences) will require reduction of emissions by the middle of the 21st century by approximately 40–70% as compared with 2010 and their cutting practically to zero by the end of the century [1].

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Danger of potential climate changes is officially recognized in Russia and readiness is expressed both to establishing international cooperation in this field and to unilaterally undertaking measures for reduction of greenhouse gases emissions [2].

"Cost" ("price", "shadow price") of carbon dioxide equal to the expenditures required for preventing its unit emission is the important characteristic of CO_2 emission reduction plans. CO_2 cost is determined according to the results of mathematical modeling of power generation development [3–5]. If this value is instituted for enterprises as the size of payment for emissions (other option is to organize emission trading) than the correlation between economic efficiency (competitiveness) for different energy sources will be changed in favor of nuclear power plants and renewable energy sources (RES) and it will become profitable for generating companies to change the structure of their generating capacities in such a way as to comply with the required restriction imposed on the overall emission.

It is assumed that taxes on emissions will be introduced first of all by a limited number of countries making the largest contribution in the world emission of carbon dioxide and enjoying high levels of economic development [4]. System of emission trading currently exists in the countries of the European Union. Prices regulated by the market proved to be unstable: from several units to several dozens of dollars per ton CO_2.

With the current policies being pursued by countries of the European Union, in Australia, New Zealand and South Korea carbon dioxide prices will amount by 2035 to 30–50 \$/ton CO_2. Under the scenario of adoption of stricter economic restrictions (stabilization of CO_2 concentration at the level of 450 ppm (parts per million)) carbon dioxide price will be significantly higher (to 100–125 \$/ton CO_2 by 2035) [4].

Cost of electricity

Competitiveness of electric power plants of different types is determined in the first approximation by the cost of electricity [6–9]. This cost can be presented as the sum of components accounting for the cost of construction, annual operational costs, decommissioning costs, fuel costs, as well as payments for emissions as follows:

$$S = \frac{k}{(CF \times H(1-\beta))}\left[\frac{F(\exp(\sigma\Delta T)-1)}{[(\sigma\Delta T)+\delta+(F-\sigma)\varepsilon]}\right] + \frac{p\sigma/(\sigma-\mu)+ap*}{11.7\times 10^3\eta},$$

where k is the specific capital cost, \$/kW; CF is the capacity factor; H is the number of hours per year (8760 h/yr); β is the energy consumption to cover internal needs of the plant (fraction of production); $F=\sigma/(1-\exp(-\sigma T))$ is the capital recovery factor; $\sigma=\ln(1+d)$; d is the annual discount rate; T is the service life of the energy source, years; ΔT is the duration of construction, years; δ, ε are the annual fixed expenses and dismantling costs (fraction of capital investments), respectively; p is the fuel price, \$/toe; η is the efficiency; $\mu=\ln(1+\nu)$; ν is the annual rate of fuel price increment; a is the emission factor, t CO_2/toe (a = 2.8 for coal and 1.7 for gas); $p*$ is the price of carbon dioxide emissions, \$/ton CO_2.

Use of electricity cost criterion is justified for evaluation of power generating technologies efficiency when it is required to exclude economy of scale effects of the power generation project from the results of investigation (in contrast to the net present value criterion) and to determine quality of the project using specific indicators. The best among several energy sources is the one ensuring the least cost of electricity produced.

Comparison of parameters of nuclear and non-nuclear energy sources

Technical and economic indicators of modern and potential energy sources are characterized by significant uncertainty. Taking into account non-uniformity and insufficient reliability of the published indicators when used as information sources it is reasonable to use publications of the recognized organizations containing data collected and processed using unified methodology [9,10].

It was assumed that the examined projects include the new power plants to be commissioned in 2015 (in Russia and in other countries) and power plants continuing their operation during the whole established service life (20 years and more). Thus, the data refer to energy sources of different types operated in different economic and geographic conditions during the period lasting from the present moment until the second or the third quarter of the 21st century.

The following power generation technologies are examined: electric power plants operated on coal or natural gas, nuclear power plants and renewable energy sources.

Coal (bituminous and lignite coal) fueled electric power plants are consisted for the most part of power units with super-critical and ultra-supercritical steam parameters with unit power equal to 300–1000 MW and with efficiency of 40–45%. Power plants operated on natural gas include combined cycle gas turbine units in 14 countries; they require lesser capital investments compared to coal power units, have lesser carbon dioxide emissions and higher efficiency reaching up to 59%.

As applied to nuclear power generation the collected technical and economic indicators characterize 20 light water reactors in 12 OECD countries, three countries non-members of the OECD and three industrial organizations including 17 pressurized water reactors, two boiling water reactors and the project of third generation nuclear reactor of General Electric Company. Power units have, as a rule, electric power equal to 1000–1600 MW.

In connection with the fact that cost of transportation of nuclear fuel does not add significant contribution to total expenses this cost was accepted to be the same and equal to some average value.

Only wind and solar power installations were selected from wide enough spectrum of RES. It is explained by the fact that

Table 1
Indicators for electric power plants.

	CF, %		k, \$/kW		Efficiency, %		δ, %	T, years
	min	max	min	max	min	max		
For foreign conditions								
Nuclear	80	85	2800	5500	33	35	4.3	60
Coal	80	85	1800	2700	33	47	2.0	30
Gas	80	85	720	1420	38	59	2.7	40
Wind	20	41	1800	2700	25	35	2.6	25
Solar	10	25	2500	4000	14	20	0.6	25
For Russian conditions								
Nuclear	80	85	2500	3500	33	35	4.3	60
Coal	80	85	1700	2500	42	47	2.0	30
Gas	80	85	1050	1420	45	55	2.7	40
Wind	20	32	1600	2200	25	35	2.6	25
Solar	10	15	2500	5000	14	20	0.6	25

RES have, for the most part, very specific characteristics depending on the place of their installation that make their comparison with energy sources of other types located in other areas meaningless.

Specific capital investments, capacity factor (for RES), efficiency and fuel price (for electric power plants operated on fossil fuel) have the most significant impact on competitiveness of energy sources. Main technical and economic parameters of the compared electric power plants are presented in Table 1 taking into account the uncertainty margins according to the data in [9,10]. Here and below values of economic indicators are given in constant prices of 2010.

The most important indicator for nuclear power plants, i.e. specific capital investments, differs in Russia from the indicators for foreign, especially European, power plants because of different structure of costs (see Table 1). Because of this reason it is justifiable to address the data for Russia separately.

In connection with the fact that electric power plants commissioned in 2015 will be then operated during several decades it is necessary to additionally take into account medium- and long-term price dynamics [11]. This is especially important for fossil fuel in connection with gradual depletion of deposits of cheaper grades of these fuels and the need to extract more and more expensive resources [3,12]. Beside that in the conditions of Russia, with its large expanses and territorial non-uniformity of energy resources distribution, accurate taking into account the regional specifics of different types energy sources is very important [6,7,11].

At the assessment of effectiveness of energy sources price of nuclear fuel was accepted to be equal to 0.8–0.9 cent/kWh (price for Russia – 0.3–0.4 cent/kWh), coal price – to 136–163 \$/toe (price for Russia – 50–119 \$/toe), price of natural gas – to 279–315 \$/toe (price for Russia – 107–196 \$/\$/toe). Price increase was accepted to be equal to 0.6–1.7% a year [11]. Such price increase corresponds to the objective trends of the world fuel and energy complex development which, in the final run, will produce more significant influence on the prices as compared with short-term effects of political factors [12].

It was assumed that period of construction amounts for NPP to seven years, that for coal electric power plants is equal to four years, for gas electric power plants to two years and for RES to one year; decommissioning costs are equal to 15% of initial capital investments for NPP and to 5% for other energy sources; this costs are spread over the period of 10 years.

Results of calculations for discount rate $d=7.5\%$ are presented in Figs. 1 and 2. Two options were examined, namely, for foreign and for Russian conditions.

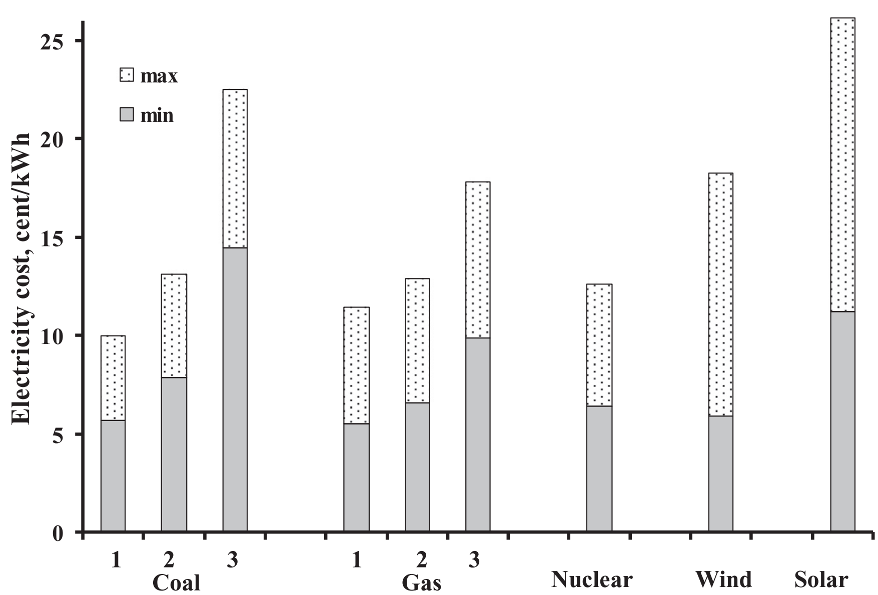

Fig. 1. Cost of energy for electric power plants of different types for foreign conditions (1 – without payment for emissions; 2 – payment for emissions equal to 30 \$/t CO_2; 3 – payment for emissions equal to 120 \$/t CO_2).

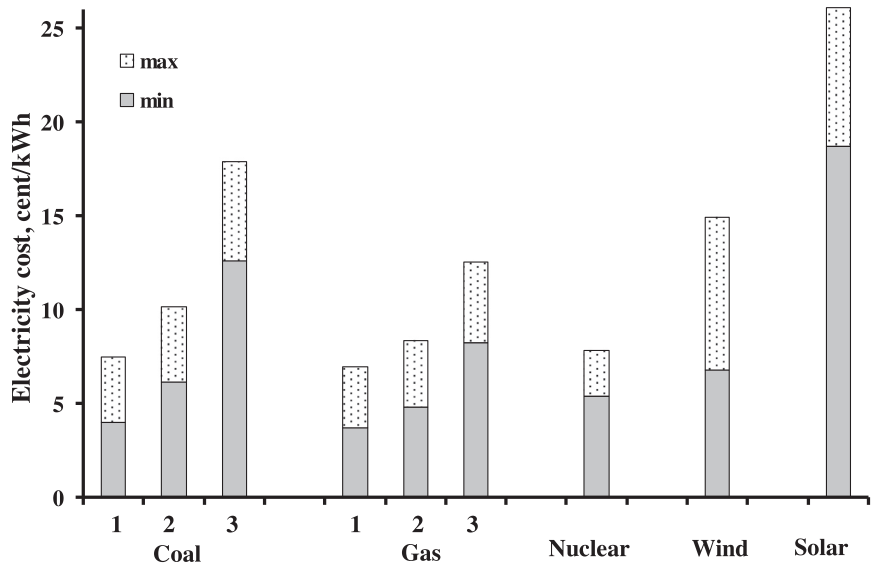

Fig. 2. Cost of energy for electric power plants of different types for Russian conditions (1 – without payment for emissions; 2 – payment for emissions equal to 30 \$/t CO_2; 3 – payment for emissions equal to 120 \$/t CO_2).

Payment for carbon dioxide emissions was determined on the basis of mathematical modeling results [3–5] for the following three scenarios:

1 –without imposition of restrictions on CO_2 emissions; price of emissions in this case $p{*}=0$ \$/t CO_2;
2 –with imposition of moderate restrictions (37 Gt CO_2 in 2030 and 45 Gt CO_2 in 2050), $p{*}=30$ \$/t CO_2;
3 –with imposition of strict restrictions (30 Gt CO_2 in 2030 and 15 Gt CO_2 in 2050), $p{*}=120$ \$/t CO_2.

As it is clear from the results of calculations, coal, gas, nuclear and wind electric power plants without payment for emissions can appear to have equal economic efficiency – uncertainty margins for cost of electricity are overlapping. Therefore priority in each case must be given to the option detailed assessment for which was implemented taking into account the local specifics and strategic goals of the energy policy of the country: efficient use of difficult to extract resources, diversification of energy supplies, energy security, social and economic efficiency, creation of conditions for transition to sustainable development, etc.

Competitiveness of NPP and wind power plants is improved taking into account payments for emissions. With $p^{*}=120$ \$/t CO_2 cost of electricity for coal electric power stations is increased by more than two times and such power plants in all cases cannot compete with NPPs. With such rate of payments for emissions gas power plants are still capable to compete with NPP, although on the average they will be less efficient. Wind power plants can produce cheap enough electricity, but, at the same time, use of back-up capacities is required because of stochastic character of this type of energy resources. Energy produced by solar electric power plants remains to be too expensive under the applied technical and financial indicators.

Forecast of development of nuclear power generation in Russia and in the world

For competitiveness assessment of nuclear power plants it is not sufficient to limit the study to the comparison of energy cost of different energy sources. It is necessary as well to take into account the influence of systems effects resulting from interaction of energy utilities, additional conditions and restrictions. The latter include restrictions on the energy consumption levels, production of different fossil fuels, emissions of hazardous substances, electricity consumption patterns (operation within base and peak parts of load curves), possibility to use nuclear power not only for production of electricity, but, as well, for production of heat and secondary energy carriers (hydrogen), necessity of back-up capacities to compensate stochastic energy production of wind and solar power plants, restrictions on the rates of growth for separate types of technologies, etc.

Systems effects are usually taken into consideration by application of mathematical models, use of scenarios developed to account for the uncertainty of information on the future conditions of energy development.

Dynamic version of GEM mathematical model (global energy model) was applied in the present study for assessment of competitiveness of nuclear and non-nuclear energy sources [12]. The model describes power generation industry in the form of interrelated processes (technologies) of extraction or production of primary energy resources (oil, natural gas, coal, uranium, renewable energy sources), their conversion into secondary energy carriers (motor fuel, synthetic natural gas, methanol, hydrogen, etc.) and production of final types of energy (electricity, heat, mechanical and chemical energy) [3,12].

Values of specific capital investments for commissioning of industrial objects, operational costs, final product yield per unit consumed resource (efficiency), yield of accompanying products (hazardous substances), and some other characteristics are set for each of the examined technologies. Nuclear power generation is presented in the GEM model by uranium extraction technologies, production of electricity by NPPs equipped with thermal and fast reactors, production of heat by heat supply nuclear power plants, conversion of nuclear power into hydrogen. Uranium extraction is presented in the form of technologies with different uranium extraction process ranging from 14 to 53 \$/toe, which approximately corresponds to fuel component of electricity cost equal to 0.4–1.3 cent/kWh.

Energy system is characterized by sets of nodes (regions) $R = \{1, \ldots, r_u\}$, technologies $J = \{1, \ldots, j_u\}$, as well as by aggregations of load curves, environment contaminants, energy resources (primary and secondary), final types of energy, final products (services) and non-energy factors (for instance, investments). Each technology j from the list J in region $r \in R$ during the period $t \in T$ is characterized by installed capacity (productivity) X_{trj} and by specific costs C_{trj}.

The interval of system development T under examination is divided into t_u periods $T=\{1, \ldots, t_u\}$ with duration $\Delta\tau_t$ each. Duration of periods can be variable. It is necessary to find such program of the world energy system development (vector x_{opt}) within time interval T, which would produce minimum value of the object function Z. Overall costs of development and functioning of the world energy system within the time interval T were selected as the object function.

Mathematical description of technological structure development of the world energy system can be presented as the problem of mathematical programming in the following form:

Find minimum of object function:

$$Z = \Sigma_t \Sigma_r \Sigma_j C_{trj} X_{trj}, \forall t \in T, \forall r \in R, \forall j \in J$$

meeting the conditions associated with ensuring coverage of consumer needs in energy and peak loads, balance between production and consumption of energy carriers and a number of imposed restrictions (financial, on the use of non-renewable energy resources and others) [3,12].

Three scenarios similar to those presented above (1 – without imposition of restrictions on emissions, 2 – with soft restrictions, and 3 – with rigid restrictions) were formulated for performing calculations using the model. Results of calculations are presented in Figs. 3 and 4.

Under the first scenario fossil fuel, and first of all coal, remains during the whole forecasted period to be the basis of the world power generation. Coal-fueled power plants and boilers playing important role in electricity and heat production act in this scenario as the main source of carbon dioxide. Stiffening restrictions on the emissions leads to the reduction of organic fuels consumption, especially coal. On the other hand, consumption of nuclear energy and renewable energy is significantly increased.

Performed calculations demonstrate that depending on the external conditions of world energy development, in particular, imposition of restrictions on greenhouse gases emissions, the need to commission fast breeder reactors will appear already during the first quarter of the 21st century [12–18].

In accordance with performed calculation fraction of NPPs in the world production of electricity must increase to reach 17–24% by the middle of the century (Table 2). Fraction of NPPs in Russia will be even higher due to the fast transition

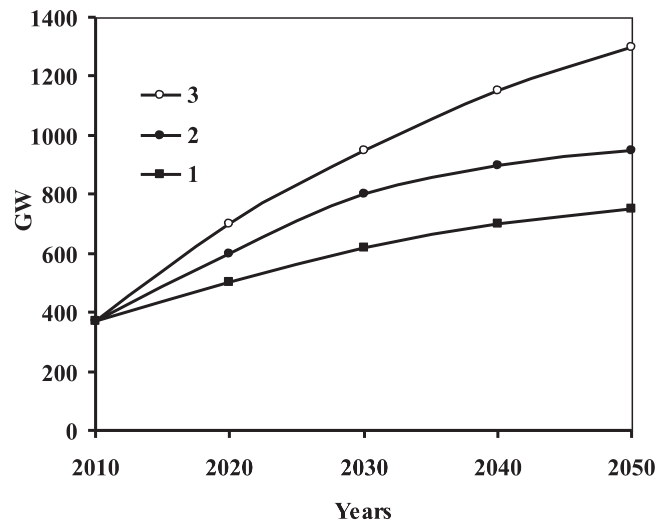

Fig. 3. Installed capacities of NPPs (GW) in the world for three scenarios.

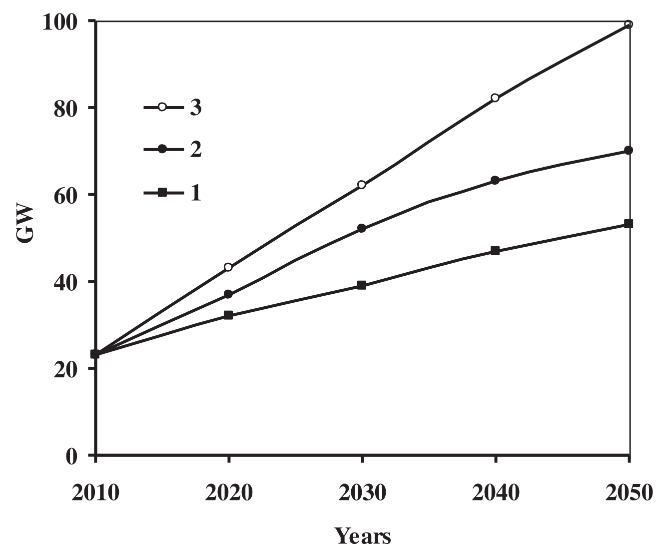

Fig. 4. Installed capacities of NPPs (GW) in Russia for three scenarios.

Table 2
Electricity production (10^{12} kWh/yr) and fraction of NPP (%).

	Years 2010	2030	2050
World, total	18.2	29–32	36–42
Including NPP	2.6	5–7	6–10
Fraction of NPP, %	14	17–22	17–24
Russia, total	1.0	1.3–1.6	1.6–2.0
Including NPP	0.2	0.3–0.5	0.4–0.7
Fraction of NPP, %	17	23–28	25–36

to the use of fast reactors and will amount to 25–36% by the middle of the century.

The presented forecasts reflect the optimal scales of development of nuclear power generation in accordance with economic criterion. They are valid within the framework of the examined scenarios. In the present study scenario with low fossil fuel prices which recently started to be realized was not examined. Such approach is justified by the fact that such scenario is to a significant extent associated with non-economic factors and in long-term perspective growth of fossil fuel prices will be inevitable because of depletion of resources of fossil fuels. Beside that in case of introduction of environmental restrictions enhancement of competitiveness of NPP and RES will occur at any fuel prices.

Conclusion

1. Comparison was made of electric power plants economic efficiency taking into account the parameters uncertainty. It was demonstrated that without payments for emissions energy sources of all the examined types can be competitive on energy markets (under certain conditions), including markets in Russia. Implementation of more expensive solar electric power plants is motivated, mainly, by not-economic factors.
2. If payment for emissions of greenhouse gases is taken into account competitiveness of NPP and RES is improved, and nuclear power plants become the most cost efficient source of energy.
3. Additional comparison of energy sources of different types taking into account the systems effects was implemented using the GEM model. Calculations demonstrate that in all examined scenarios the scale of nuclear energy use is expected to increase. This growth – by four times in Russia and by 3.5 times in the world – will be the most significant in case of adoption of strict environmental restrictions.

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